

Diversity and impacts of key grassland and forage arthropod pests in China and New Zealand: An overview of IPM and biosecurity opportunities

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Abstract

For both New Zealand and China, agriculture is integral to the economy, supporting primary production in both intensive and extensive farming systems. Grasslands have important ecosystem and biodiversity functions, as well providing valuable grazing for livestock. However, production and persistence of grassland and forage species (e.g. alfalfa) is not only compromised by overgrazing, climate change and habitat fragmentation, but from a range of pests and diseases, which impose considerable costs on growers in lost production and income. Some of these pest species are native, but increasingly, international trade is seeing the rapid spread of exotic and invasive species. New Zealand and China are major trading partners with significant tourist flow between the two countries. This overview examines the importance of grasslands and alfalfa in both countries, the current knowledge on the associated insect pest complex and biocontrol options. Identifying similarities and contrasts in biology and impacts along with some prediction on the impact of invasive insect species, especially under climate change, are possible. However, it is suggested that coordinated longitudinal ecological research, carried out in both countries using sentinel grass and forage species, is critical to addressing gaps in our knowledge of biology and impact of potential pests, along with identifying opportunities for control, particularly using plant resistance or biological control.

Keywords

alfalfa, biodiversity, climate change, pathways, invasive alien species, plant biosecurity, sentinel plants, pest risk analysis, international trade

Introduction

Grasslands can be defined as “terrestrial ecosystems dominated by herbaceous and shrub vegetation and maintained by fire, grazing, drought and/or freezing temperatures” (White et al. 2000). Natural grassland ecosystems are important for both ecological functioning and biodiversity conservation (Mark et al. 2013; Pfeiffer et al. 2018). They contribute to water supply and management, soil organic C storage, erosion control and climate mitigation (Bengtsson et al. 2019; Sollenberger et al. 2019), as well as supporting extensive faunal communities that often have high levels of endemism (White et al. 2000; Wu et al. 2015). They can also be culturally important, supporting traditional lifestyles and have educational, scientific, recreational and tourism values (Mark et al. 2013). Economically, both natural and modified grasslands are critical for food production (O’Mara 2012).

China (along with Mongolia) hosts some of the world’s largest continuous grasslands. These are largely natural swards dominated by *Leymus chinensis* (Trin.) Tzvel (sheep grass or Chinese lyme grass) with human modification to its composition occurring to a limited extent (Pfeiffer et al. 2018), but with significant habitat degradation due to climate change and overgrazing (Schönbach et al. 2011; Li et al. 2012; Wu et al. 2015; Lv et al. 2019; Zhou et al. 2019). Chinese natural grasslands cover a vast territory (Figure 1) and are conservatively estimated to cover approx. 2.8 M km² (Pfeiffer et al. 2018) or ca. 40% of the land area of China. The Provinces of Qinghai, Gansu and the autonomous regions Inner Mongolia (Hulunbuir Prairie and Xilینگol Prairie), Xinjiang (Yili grassland) and Tibet (Naqu Alpine grassland) are the main grassland regions in China, with four main ecosystem types: meadow steppe; typical steppe; desert steppe; and alpine steppe (Kang et al. 2007). The Inner Mongolian grassland is classified as temperate steppe, with native species dominated by *Cleistogenes squarrosa* (Trin.). Ken, *L. chinensis* and *Stipa krylovii* Roshev., *Artemisia frigida* Willd. and *Caragana microphylla* Lam. (Leguminosea). In addition to grasslands, the introduction of crop species to Inner Mongolia has been used to support livestock, such as horses, sheep, goats and camels (Wu et al. 2015; Pfeiffer et al. 2018).

In New Zealand, grasslands comprise natural areas (variously dominated by native *Poa* spp., *Festuca* spp., *Carex* spp. or *Chionchloa* spp.), modified native grasslands consisting of native and introduced or volunteer exotic species and cultivated and sown pastures consisting almost entirely of exotic grass species (predominantly *Lolium* spp. L.) and legumes (clovers (*Trifolium* L. spp.), *Medicago sativa* L. (alfalfa, lucerne)) (hereafter ‘improved grasslands’ or pastures). These highly modified environments cover about 0.11 M km² and comprise 41% of New Zealand’s land area

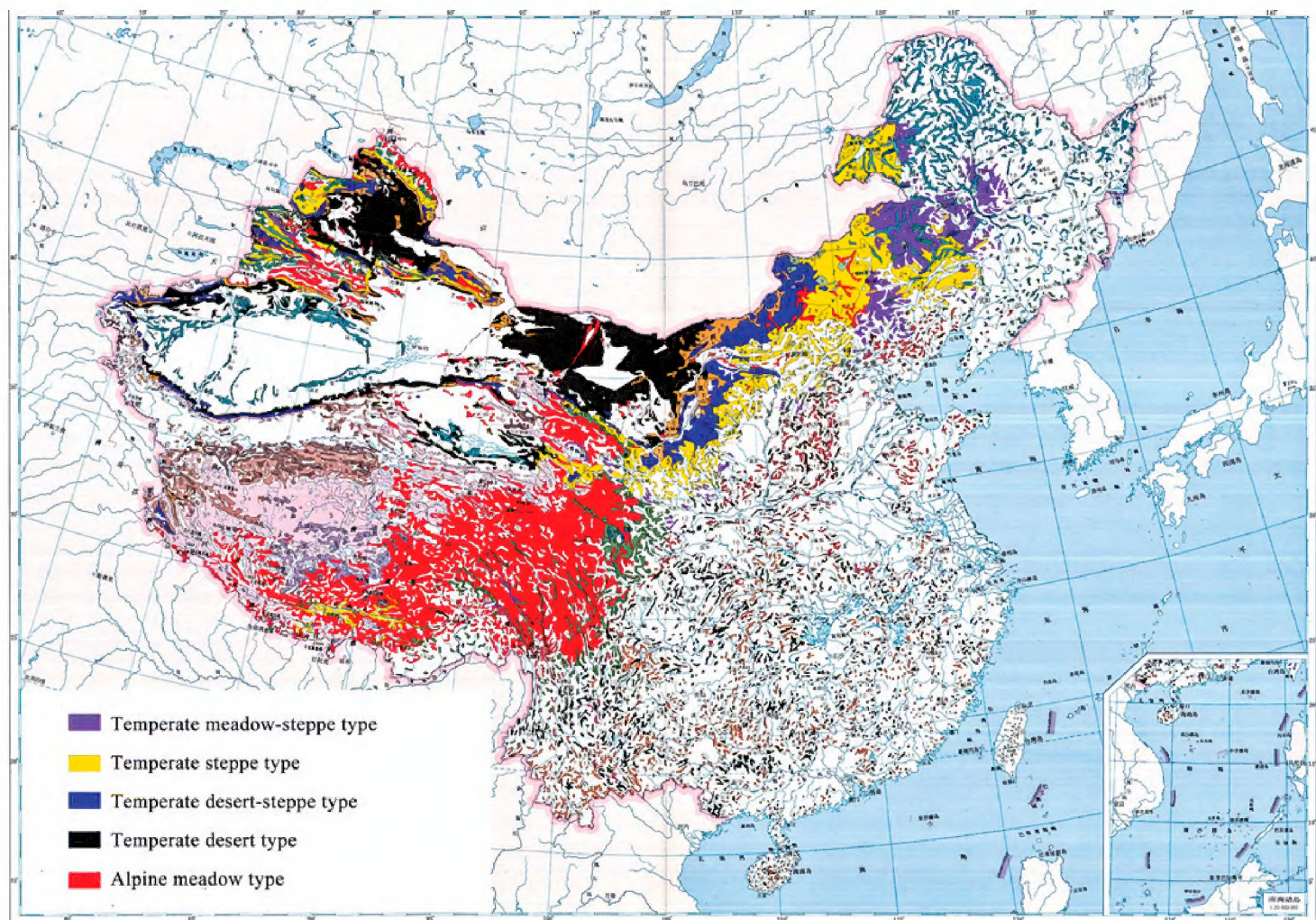


Figure 1. Map of China, showing the geographic distribution of the main grassland types. The four most extensive and important grasslands in China are indicated by (1) temperate meadow-steppe, (2) temperate steppe, (3) temperate desert-steppe, (4) temperate desert and (5) alpine meadow.

(Ferguson et al. 2018). The precise composition of improved grasslands depends on climate, farm type and topography and ranges from annual monocultures (e.g. *Festuca perennis* Lam. (formerly *Lolium multiflorum*)) to perennial combinations of generally no more than five sown plant species (e.g. perennial ryegrass (*Lolium perenne* L.), white clover (*Trifolium repens* L.), red clover (*T. pratense* L.), chicory (*Cichorium intybus* L.) and plantain (*Plantago lanceolata* L.). Perennial legumes form a critical component of improved grasslands, as they fix atmospheric nitrogen (N) and make it available to other plants, reduce the need for artificial N inputs and provide protein for grazing animals (Peoples et al. 2017, 2019).

This overview examines the role that grasslands and the forage crop alfalfa have in both countries, comparing and contrasting land use and management of important insect pests. We focus on species that have been identified from both English and Chinese language literature, as having a significant impact on grassland and forage production systems. Where possible, information on biological control agents, associated with these pests, was also collated. Finally, we discuss approaches to developing a better understanding of potential biosecurity threats which these pest species may have, if trade and tourism pathways facilitate their movement between the two countries and subsequent establishment.

Data acquisition

Information on insect pest species was obtained by searching peer-reviewed literature in English and Chinese scientific databases. The databases used were Scopus, CAB Abstracts, Chinese National Knowledge Infrastructure (CNKI) and WanFang Data. Search strategies included English, Latin and Chinese terms. These included generic keywords, such as alfalfa/lucerne and ryegrass, *Lolium spp.*, *Leymus spp.*, New Zealand, China, grassland insect pests, biological control agents and also more specific searches by insect (e.g. *Oedaleus asiaticus*, *Sminthurus viridis*) or plant (e.g. *L. perenne*, *L. chinensis*) species. A basic search strategy combined Insect (genus / species) AND Plant (genus / species) AND Country (China / New Zealand). The search results were then analysed and selected for relevancy. If the insect-plant association was not able to be determined, then the item was excluded from the search results. These databases were augmented by internal reports held by the authors' respective research organisations.

Grassland and forage ecosystems

China

China has a rich diversity of forage plants comprising 2581 species in 364 genera and 65 families, including 57 grass species in 28 genera and 56 legume species in 24 genera. Of these, 14 species are commonly cultivated (Yan et al. 2008). The main commercial forage crops grown in China include *L. chinensis*, of which 1.31 M tonnes are produced per annum (p.a.), *M. sativa* (1.43 M tonnes p.a.), *Zea mays* L. (silage corn) (0.53 M tonnes p.a.) and *Lolium spp.* (0.30 M tonnes p.a.) along with *Avena sativa* L. (Oats) (0.47 M tonnes p.a.) (Yun and Song 2017).

In Inner Mongolia and western northeast China, awnless brome (*Bromus inermis* Leyss.) is grown in a range of environments, including forest edge meadows, hill country and riverside roads. The grass has high nutritional value, good palatability, is tolerant to grazing and is cold hardy. It is also used to stabilise erosion-prone sandy areas. Fescue (*Festuca spp.* L.) is grown in alpine meadows, hillside grasslands, forests, thickets and sandy soils at an altitude of 2200–4400 metres above sea level, to provide forage for cattle, sheep and horses. The Xilin River system represents a typical inland river found in Inner Mongolia grassland. Originating in the Keshiketen Banner of Chifeng City, the river flows southeast to northwest, finally feeding into the Chagan Naoer wetland. The Xilin River Basin covers an area of approximately 10,000 km² with distinct landscape form and diverse plant communities (Tong et al. 2004). The dominant grass species are *L. chinensis* and *Stipa grandis* P. Smirn, along with *Agropyron cristatum* (L.) Gaertn, *Achnatherum sibiricum* (L.) Keng ex Tzvelev, *Koeleria cristata* (Linn.) Pers., *C. squarrosa* and *Carex korshinskyi* Kom. (Zhang et al. 2014).

In improved dairy and sheep grasslands in China, the main grass species are *Z. mays*, perennial ryegrass L. and annual ryegrass, *Elymus dahuricus* Turcz. ex Griseb and *E. sibiricus* L., *Bromus inermis* Leyss. and cocksfoot (*Dactylis glomerata* L.). The

predominant legumes are *M. sativa*, erect milkvetch (*Astragalus adsurgens* Pall.), common sainfoin (*Onobrychis viciaefolia* Scop.), *T. repens*, *T. pratense* and common vetch (*Vicia sativa* L.). Oats *Avena sativa* L., sudan grass (*Sorghum sudanense* (Piper) Stapf.) and sorghum (*S. bicolor* (L.) Moench) are also grown for forage. While the economic value of these main forage plant species is not available, the area grown and yields are shown in Suppl. material 1: Table S1.

Alfalfa is perennial leguminous forage, valued in China as a high-quality feed for livestock and poultry. Since 2000, China has been returning farmland to forest and grassland to reduce water and wind erosion in areas prone to these phenomena (Zao et al. 2012). As a result, the area planted in alfalfa has successively expanded as it is regarded as an important part of the restoration of regional ecological environments and because it is seen as integral to the transformation of traditional agricultural, by increasing farmers' income and promoting social and economic development (Zao et al. 2012; Li 2019).

New Zealand

Native grasses in New Zealand, while of some benefit for livestock grazing, are increasingly valued as iconic grassland landscape species (Mark et al. 2013). The main areas of native grasslands are found in the central North Island, but more extensively in the South Island high country (Figure 2). There are 157 grass species endemic to New Zealand with an additional 31 indigenous species with a shared distribution in Australia and other Pacific Islands (Edgar and Connor 2010). These include silver tussock (*Poa cita* Edgar), fescue tussock (*Festuca novae-zelandiae* (Hack.) Cockayne), several *Chionochloa* spp. (e.g. *C. rigida* (Raoul) Zotov, *C. rubra* Zotov, *C. flavescens* Zotov and *C. pallens* Zotov) and *Carex* spp. (e.g. *C. buehnanii* Bergg. and *C. dipsacea* Bergg.). Tussock grasslands deliver a wide range of important ecosystem services that provide many tangible benefits to human well-being but have generally not been quantified or evaluated (Mark et al. 2013). In addition, these biomes support endemic invertebrate communities that may be unable to adapt to modified grasslands and face displacement by exotic invaders, for example, 25 of New Zealand's 26 terrestrial amphipod species are endemic with evidence that they are being displaced in areas where an Australian invader, *Arcitalitrus sylvaticus* (Haswell) is present (Duncan 1994; Lowry and Myers 2019).

Based on 2018 data, New Zealand's agricultural production utilises 13.7 M ha (7.5 M ha in grassland and 2.4 M ha in native tussock or Rytidosperma), of which 8.8 M ha supports sheep and beef farming and 2.4 M ha dairy farming and 0.26 M ha deer farming (Anon 2020). Total agricultural exports in 2018-19 had an estimated value of NZ\$34.16 B (Free On Board (FOB)) of which pastoral exports were worth an estimated \$24.4 B (FOB) (Anon 2020). However, this is impacted, on average, by estimated losses to insect pests of NZ\$2.3 B p.a. (Ferguson et al. 2019).

Intensively developed New Zealand pastures consist of combinations of plant species predominantly based on a grass/legume mix. The most extensively used species are

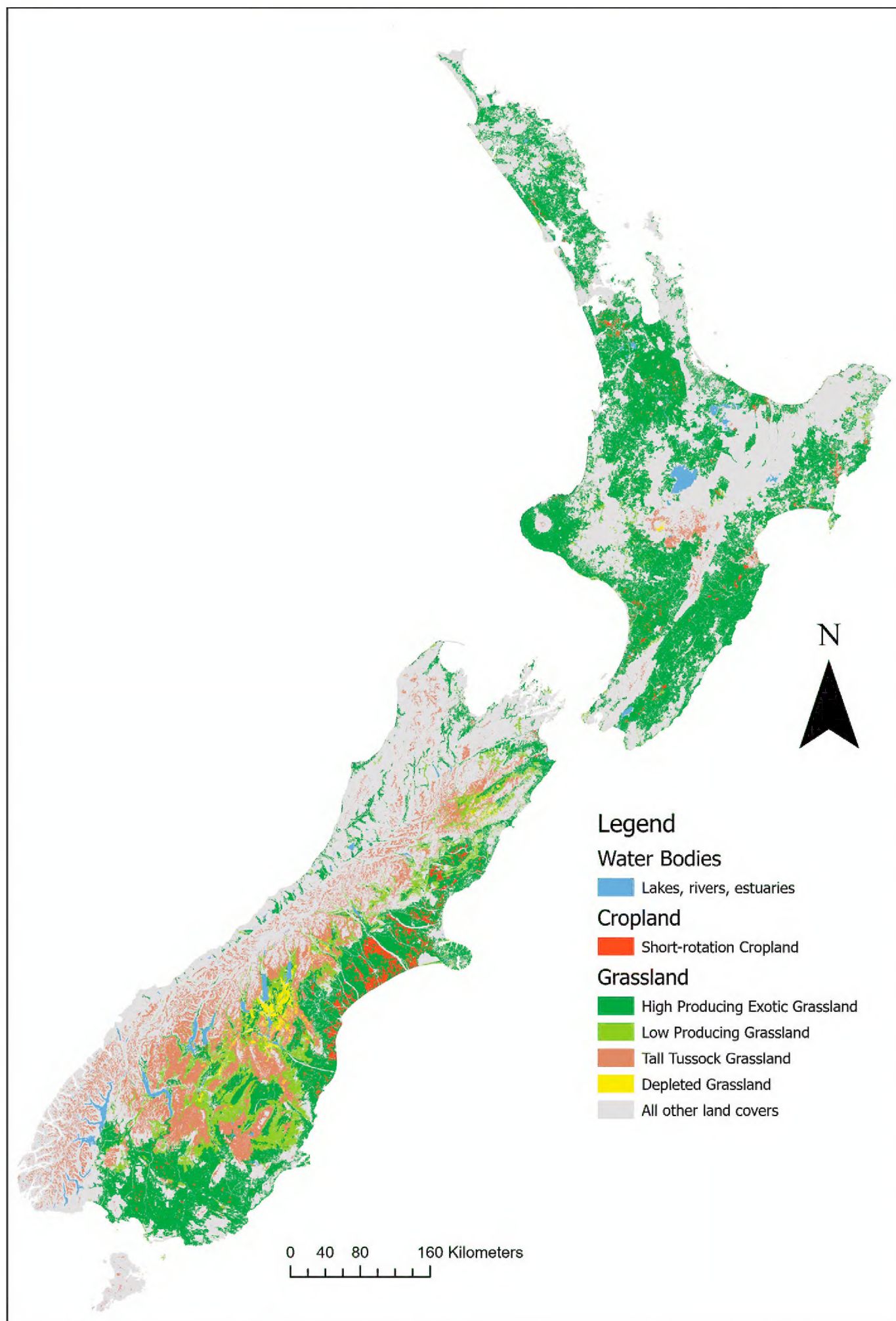


Figure 2. Map of New Zealand, showing the geographic distribution of the grassland and crop, land use classes. Land use classes sourced from the New Zealand Land Cover Database (LCDB), using New Zealand's 1:50,000 topographic database (<https://www.linz.govt.nz/land/maps/topographic-maps/topo50-maps>). Reference: Thompson S, Gruner I, Gapare N (2003) New Zealand Land Cover Database Version 2: Illustrated Guide to Target Classes, Version 5.0_January 2020, 126 pp.

perennial, short rotation hybrid and annual ryegrasses (*Lolium* spp.) and white clover. Other pasture species are tall fescue (*Schedonorus phoenix*), cocksfoot, timothy (*Phleum pratense*), red clover, chicory (*Chicorium intybus*) and plantain. In less developed pastures, browntop (*Agrostis capillaris* L.) is heavily utilised.

Alfalfa is an important dryland species used for grazing and stored winter forage. It is particularly valuable to farmers in environments where conventional ryegrass-white clover plant species cannot persist (Avery et al. 2008; Moot 2012). Alfalfa is grown across 200,000 ha producing approximately 12 tonne/ha and additionally fixing 30 kgN/tonne of legume grown. Animal production from alfalfa is approximately 700 kg of red meat per ha (D. Moot, Lincoln University, pers. communication). Other pasture legumes also grown in New Zealand for dryland farming, but on a limited scale, are Caucasian clover (*T. ambiguum*) and subterranean (*T. subterraneum*) and balansa (*T. michelianum*) clovers (Moot 2012).

Supplementing grazing pastures, fodder brassicas (*Brassica rapa*, *B. napus* and *B. oleracea*), fodder beet (*Beta vulgaris*) and ryecorn (*Secale cereale*) are sown for specialised winter grazing, while maize is greatly utilised for silage. Cereals (wheat *Triticum* spp, barley (*Hordeum vulgare*) and oats, although predominantly grown as grain crops, are also produced for silage. The value of the main forage plant species to New Zealand is shown in Suppl. material 2: Table S2.

Insect pests and impacts

China

Much of the research on grassland pests has focused on the Inner Mongolian Plateau (Le et al. 2007) and, to a lesser extent, the Tibetan Plateau (Wang and Fu 2004). In Inner Mongolian native grasslands, the herbivorous insect species complex is dominated by 96 species of grasshoppers and locusts (Orthoptera: Acrididae) and these comprise the major pest group. The key pests are *Oedaleus asiaticus* Bey-Bienko, *Calliptamus abbreviatus* Ikonn and *Dasyhippus barbipes* (Fischer-Waldheim) (Tu et al. 2015), especially on *L. chinensis*, oats and fescue in the Inner Mongolia, Xinjiang and river valleys in the eastern Qinghai-Tibet Plateau. In recent years, *O. asiaticus* has shown gregarious and migrating behaviour similar to that of the oriental migratory locust (*Locusta migratoria manilensis* (Meyen)) and has become one of the most damaging pests in northern China, at times accounting for over 90% of all grasshopper populations. On average, grasshoppers damage over 20 M ha of rangeland and forage crops p.a., consuming 1.6 M tonnes DM p.a. at an estimated cost of US\$80 M p.a. (Zhu 1999) (equivalent to US\$124 M in 2020 (813 M CNY or NZ\$172M)). Another assessment by Hong et al. (2014) estimated losses attributable to grassland locusts at 1.6 B CNY p.a. from 2003 to 2012. On the Qinghai-Tibetan Plateau, larvae of a species complex of the genus *Gynaephora* (Lepidoptera: Lymantridae) (Yuan et al. 2015), are significant pests of grasslands (Yan et al. 2006; Zhang and Yuan 2013). In 2003, an outbreak in the Qinghai Province was estimated to cover an area of 1 M ha², leading to a loss of over

90 M CNY (Zhang and Yuan 2013). In addition, the presence of cocoons in the litter can cause skin irritations and blisters to livestock (Yan et al. 2006).

Larvae of several other Lepidoptera also damage grasslands. These include the beet webworm (or meadow moth) (*Loxostege sticticalis* (L.)), the northern armyworm (*Mythimna separata* Walker) and the fall armyworm (*Spodoptera frugiperda* (J.E. Smith)). *Loxostege sticticalis* is a widely distributed, polyphagous, migratory species (Wei et al. 1987; Sun et al. 1995) that can cause significant losses in grasslands and forage crops during outbreak years (Hong et al. 2013; Tu et al. 2015). A list of key pest species in grassland and alfalfa in China can be found in Suppl. material 3: Table S3.

For alfalfa, the main pests are aphids and thrips, followed by alfalfa weevil (*Hypera postica* (Gyllenhal) (Coleoptera: Curculionidae), but published literature lists between 55 (Zhang et al. 2016) and 269 (Zhang et al. 2018) pest species, in a range of taxa and which attack all stages of the plant. Aphids and thrips are the most widespread taxa throughout the alfalfa growing regions, while *H. postica* is significant in the Ningxia and Xinjiang regions. Other pests include: *Heliothis virescens* (Hufnagel) (= *Heliothis dipsacea*) (He et al. 1997) and beet webworm (*Loxostege* sp.) (Zhang et al. 2005a). Both aphids and thrips reduce the yield and nutritional value of damaged alfalfa (Zhang et al. 2005b; Wu et al. 2013; Zhang et al. 2017) and also vector viral plant diseases. Aphids have been reported to transmit alfalfa mosaic virus (AMV), alfalfa leaf curl virus (ALCV) and bean mosaic virus (Garran and Gibbs 1982; Roumagnac et al. 2015; Ryckebusch et al. 2020) and recently two viruses (AMV and *Medicago sativa* alphapartitivirus 1 (MsAPV1)) have been identified in thrips (Li et al. 2021). The main aphid pest species are the blue alfalfa aphid (*Acyrtosiphon kondoi* Shinji), cowpea aphid (*Aphis craccivora* Koch), pea aphid (*Acyrtosiphon pisum* (Harris)) and spotted alfalfa aphid (*Therioaphis trifolii* (Monell)). The major thrips species is *Odontothrips loti* (Haliday) while *Thrips tabaci* Lindeman, *Frankliniella occidentalis* (Perg.) and *Frankliniella intonsa* (Trybom) also cause damage.

The area sown in alfalfa is expanding year by year and the most recent data showed that, in 2017, 4.15 M ha of alfalfa were being grown with a yield of 29.3 M tonnes (National Animal Husbandry Service 2017). As the area sown in alfalfa increases, so too do the incidence and impact of insect pests. Based on 2017 data, it is estimated that alfalfa pests cause at least 20% yield loss, with an average direct economic loss of 9.144 B CNY p.a (2.03 B NZD p.a.) (Li et al. 2020). Large scale outbreaks of *T. trifolii* have been estimated to cause economic losses to growers of between 0.151 to 1.127 B USD (Wu et al. 2013). Currently, *H. postica* is considered a major constraint on alfalfa production, as currently there are no effective control measures available (Zhang 2015).

New Zealand

In New Zealand tussock grasslands, severe damage to plants by indigenous insects is uncommon although occasionally observed, for example, grass grub (*Costelytra giveni* Coca-Abia & Romero-Samper), several species of the moth commonly called porina

(*Wiseana* spp.) and striped chafer beetle (*Odontria striata* White) (Campbell 1982; Barratt et al. 1988). Similarly, the impact of exotic insects within these systems seems low, although Argentine stem weevil (*Listronotus bonariensis*) Kuschel (Coleoptera: Curculionidae) (ASW) is widespread (Murray et al. 2003) and has been shown to feed on seedling blue tussock (*Poa colensoi* Hook.f.), *F. novae-zelandiae* and narrow-leaved snow tussock (*Chionochloa rigida* (Raoul) Zotov) and, potentially, could impact on seedling survival (Barratt et al. 2016). Indigenous insects have been shown to feed on exotic plants in areas where native vegetation is largely intact; for example, the native weevils *Chalepistes* spp. (formerly *Irenimus* spp., Brown 2017) and *Nicaeana* spp. (Barratt and Johnstone 1984; Barratt et al. 1992) will feed on and damage clover and seedlings. Similarly, the same genera can be common within cultivated and sown pastures consisting of entirely exotic pasture plants, but are not known to cause significant damage to these.

Insect pests are a persistent and significant economic cost to improved grassland and forage production systems in New Zealand (e.g. Zydenbos et al. 2011; Jackson et al. 2012; Ferguson et al. 2019), with a small number having a major impact on production and longevity of pastures (Suppl. material 4: Table S4). The major pests in improved grasslands are the endemic grass grub and porina, especially *W. cervinata* (Walker) and *W. copularis* (Meyrick) (Richards et al. 2017), along with the exotic ASW, clover root weevil (*Sitona obsoletus*, Gmelin) (CRW) and African black beetle (*Heteronychus arator*) (F.) (Ferguson et al. 2019). The estimated annual costs to agriculture are shown in Table 1.

Several lesser, or locally significant, pests also impact on production and persistence: black field cricket (*Teleogryllus commodus*) (Walker) (Orthoptera: Gryllidae), clover flea (*Sminthurus viridis*) (L.) (Collembola: Sminthuridae) and African black beetle are recurrent pests in the warmer areas of North Island, while Tasmanian grass grub (*Accrosidius tasmaniae* (Hope)) is widespread and locally damaging.

In part, the significant impact caused by endemic species, such as grass grub and porina, can be attributed to the high nitrogen and low fibre content of the exotic plant species compared to the native plant hosts (e.g. Atijegbe et al. 2020). Endemic scarabs that can have significant impacts locally include species from the genera *Odontria* (e.g. *O. striata* (White)) (Ferguson et al. 2019) and *Pyronota* (e.g. *P. festiva* F. and *P. setosa* (Given)) (Townsend et al. 2018). Endemic Orthopteran species, also found in improved grasslands, include the small field cricket (*Bobilla* spp.) and grasshopper (*Phaulacridium marginale*) (Walker). Neither is considered pests.

With the relatively recent increased use of the herb, narrow leaf plantain (*Plantago lanceolata*), in improved pasture (Stewart 1996), two previously insignificant, native Lepidoteran species *Scopula rubraria* (Doubleday) and *Epyaxa rosearia* (Doubleday) have emerged as pests, particularly when plantain is grown as a monoculture (Ferguson and Phillip 2014). Other pests that can specifically affect pasture seedling establishment include several lepidopteran species, including *Eudonia sabulosella* (Walker) and *E. submarginalis* (Walker) (both referred to as sod webworm) and *Agrotis ipsilon* (Hufnagel) (greasy cutworm). The wheat bug, *Nysius huttoni* White, is an endemic spe-

Table 1. Summary of the mean annual monetary cost (NZD/CNY) of invertebrate pests to New Zealand agricultural production and the regions affected. Figures updated to 2020 costs from 2011 values¹. M = Million.

Insect species	Estimated cost (NZD M / CNY M)				Regions affected
	Dairy		Sheep & Beef		
	NZD	CNY	NZD	CNY	
Grass grub (<i>Costelytra giveni</i> Coca-Abia & Romero-Samper) *	156–425	736–2006	84–230	396–1086	All except northern North Island
Porina (<i>Wiseana</i> spp.)	78–94	368 – 443	87–99	412–466	All except northern North Island
Black beetle (<i>Heteronychus arator</i>) (F.)	165–249	778–1177	17–21	79–101	Northern North Island some coastal areas
Argentine stem weevil (<i>Listronotus bonariensis</i> , (Kuschel))	111–145	526 – 686	67–79	317–371	All
Clover root weevil (<i>Sitona obsoletus</i> , Gmelin) **	68	321	195	920	All

¹ 2020 values determined from the % change in the New Zealand consumer price index 2011 to 2020. CNY values determined from CNY/NZD exchange rates as at 31 December 2020, 1 NZD = CNY 4.72.
*includes mānuka beetle (*Pyronota* spp.) and striped chafer (*Odontria striata*, White).
**cost after suppression through biocontrol by the parasitoid *Microctonus aethiopoides*.
Table adapted from Ferguson et al. (2019).

cies often found both in native and improved grasslands and is also an invasive species (Lay-Yee et al. 1997; Aukema et al. 2005). *Nysius huttoni* has a wide host range which includes *Triticum aestivum* (wheat), several *Brassica* and *Poaceae* spp., *M. sativa*, *T. repens* and *T. pratense* (EPPO 2006) and can have significant impacts on seedling survival (e.g. Gurr 1957; Ferguson 1994).

Alfalfa in New Zealand is grown either as a monoculture, destined to be harvested for stored winter feed and, to a lesser extent, for feed pellet production or as grazing alfalfa, either as a monoculture or in combination with grass, often tall fescue. It has only a few major pests, but the key species are all exotic and comprise *Sitona discoideus* Gyllenhal (in New Zealand called lucerne weevil) and three aphid species (*A. kondoi*, *A. pisum* and *T. trifolii*). The introduction of *A. kondoi* and *A. pisum* to New Zealand was also associated with an increase in the incidence of AMV in alfalfa stands (Forster et al. 1985). Lesser pests are white fringed weevil (*Naupactus leucoloma* (Boheman)) (King et al. 1982) and the little fringed weevil (*Atrichonotus taeniatulus* (Berg)) (Barratt et al. 1998).

Insect pest management

China and New Zealand face similar pest management issues. Traditional use of insecticides is no longer seen as the best option to mitigate pest impact and more focus is being placed on integrated pest management (IPM) systems utilising biopesticides, biological control and endophytes to mitigate pest impacts.

China

In grasslands, insects, entomopathogens and birds play an important role in naturally controlling pest populations. Insect biological control agents include dipteran species within Bombyliidae, Calliphoridae, Asilidae and Syrphidae, a range of coleopteran

species of Carabidae (e.g. Tenebrionidae, Cicindelidae and Coccinellidae), neuropterans within the Chrysopidae and parasitoids. Entomopathogens include *Metarhizium anisopliae* (Metchnikoff) Sorokin, locust microsporidia (*Nosema locustae* Canning), *Beauveria bassiana* (Balsamo) Vuillemin, *Bacillus thuringiensis* Berliner and Entomopoxviruses (EPV). The former two are used extensively for grasshopper control, while *B. bassiana* and *B. thuringiensis* were mainly used for controlling soil pests, such as scarab larvae or lepidopteran larvae on foliage. These are usually applied to forage crops including maize and *M. sativa*.

Particularly in the control of locusts, pathogenic fungi and microsporidia are important in preventing the occurrence of outbreak populations. Strains of *M. anisopliae* and *B. bassiana*, specific to locusts, were introduced into China in 1990s and different formulations, such as an oil base, baits and wettable powder have been explored to optimise control in various grassland conditions. Since then, approximately 100 M hectares have been treated with *B. bassiana* (Zhang et al. 2000; Nong et al. 2007; Bian et al. 2009).

Locust microsporidium, isolated from *Locusta migratoria migratorioides* (Reiche & Fairmaire) in the 1950s, has been shown to infect over 100 locust species and other orthopterans. It significantly reduces food intake, activity, fecundity and viability of eggs and causes insect death after 15 to 20 days (Wang and Yan 1999; Wu et al. 2000; Zhang and Yan 2008). Locust poxvirus is mainly used for locust control in Xinjiang, north-west of China, where *Calliptamus italicus* L., *Gomphocerus sibiricus sibiricus* (L.) and *Dociostaurus* spp. are the dominant locust species (Wang 1994).

Rosy starling (*Pastor roseus* L., formerly *Sturnus roseus*), hens (*Gallus gallus domesticus* L.) and ducks (Anatidae) are also used for localised control of grassland pests, especially grasshoppers and locusts (Lu et al. 2006). Rosy starlings have been shown to be an effective predator, with artificial nesting boxes used extensively to support populations (China Grassland Statistics 2018). The starlings feed both during the locust breeding and growth periods, with each adult starling shown to consume 120 to 180 locusts per day. Two studies carried out in the Xinjiang Region, showed that over a breeding season, rosy starlings were able to significantly decrease grasshopper densities (Guo 2005; Ji et al. 2008). Furthermore, starlings have been shown to follow locust swarms ensuring ongoing control (Guo 2005; Yu and Ji 2007). The use of poultry by farmers for pest control mainly occurs in Inner Mongolia and Xinjiang (China Grassland Statistics 2018).

A selection of insect biocontrol agents, both native and introduced and found in grassland and alfalfa in China, is shown in Table 2.

New Zealand

In natural New Zealand grasslands, several native natural enemies provide natural population regulation of significant endemic pests, particularly grass grub and porina. However, this breaks down in improved grasslands under agricultural management, primarily due to the disruption of soil-borne pathogens following cultivation. Some natural entomopathogens do regulate populations of these insects in older pastures,

Table 2. List of insect biocontrol agents, both native and introduced found in grasslands and alfalfa in China.

Insect species	Host attacked	Pest stage attacked	Biocontrol agent origin
Coleoptera: Carabidae			
<i>Lachnocrepis prolixa</i> (Bates)	Various	Various	Native
<i>Pterostichus gebleri</i> Dejean	Various	Various	Native
Coleoptera: Cicindelidae			
<i>Cicindela chinensis</i> DeGeer	Various	Various	Native
<i>Cicindela hybrida</i> L.	Various	Various	Native
Coleoptera: Coccinellidae			
<i>Coccinella septempunctata</i> L.	Aphids	Adult and Nymphs	Native
<i>Hippodamia variegata</i> (Goeze)	Aphids	Adult and Nymphs	Native
<i>Propylaea japonica</i> (Thunberg)	Aphids	Adult and Nymphs	Native
Diptera: Syrphidae			
<i>Chrysopa sinica</i> Tjeder	Aphids	Adult and Nymphs	Native
<i>Metasyrphus corollae</i> F.	Aphids	Adult and Nymphs	Native
Hymenoptera: Braconidae			
<i>Aphidius eadyi</i> Stary, González & Hall	<i>Acyrtosiphon kondoi</i> Sinji	Nymphs	Native
<i>Aphidius ervi</i> Haliday	<i>A. kondoi</i>	Nymphs	Native
<i>Aphidius eadyi</i>	<i>Acyrtosiphon pisum</i> Harris	Nymphs	Native
<i>Aphidius ervi</i>	<i>Acyrtosiphon pisum</i>	Nymphs	Native
<i>Aphidius picipes</i> (Nees) (syn. <i>A. avenea</i> Haliday)	<i>Sitobion avenae</i> (Fabricius)	Various	Native
Hymenoptera: Eulophidae			
<i>Chrysonotomyia trifolii</i>	<i>Coleophora frischella</i> L.	Larvae	Native
Neuroptera: Chrysopidae			
<i>Chrysoplera sinica</i> (Tjeder)	Aphids	Adults and nymphs	Native

but they do not prevent pest outbreaks in young pastures (Jackson et al. 2012). Other natural enemies, for example, *Procissio cana* Hutton (Diptera: Tachinidae) which can parasitise up to 20% of third-instar grass grub larvae, are uncommon in highly modified pastures (Merton 1982). The introduction of several exotic biocontrol agents targeting these endemic pests failed (Cameron et al. 1989) and any similar attempts are now very unlikely to gain approval from New Zealand’s Environmental Protection Authority.

Two endemic entomopathogenic bacteria, *S. proteamaculans* (Paine and Stansfield 1919), Grimont et al. 1978 and *Serratia entomophila* Grimont et al. 1988 (both Enterobacteriaceae), have been found to suppress larval populations of grass grub (Hurst et al. 2000; Hurst et al. 2018). The former is the only endemic biopesticide that has been commercially developed for use against pasture pests in New Zealand, but since its availability in 1990, uptake has been low. *Serratia proteamaculans* also has activity against mānuka beetle (*Pyronota* spp.) larvae. In addition, laboratory trials where mānuka beetle larvae were treated with the entomopathogenic fungi *Beauveria brongniartii* (Saccardo) Petch, produced high rates of larval mortality (Townsend et al. 2010), although formal field trials to determine efficacy have not been undertaken. Several porina-active microbial pathogens have been identified, including fungi, protozoa, viruses and nematodes (Bourner et al. 1996). The fungus, *M. anisopliae*, can cause infrequent epizootics of larvae (Latch and Kain 1983). The entomopathogenic bacterium, *Yersinia entomophaga* Hurst et al., 2011, isolated from grass grub has been shown in laboratory and field trials to have high levels of pathogenicity against larvae of two species of porina: *W. cervinata* and

W. copularis (Hurst et al. 2019). However, attempts to commercially produce formulations of indigenous pathogens, targeting these pests, are largely thwarted by the small market size and the relatively high cost of development (Glare and O'Callaghan 2019).

Three braconid parasitoids from the genus *Microctonus* have been introduced to provide biological control of three exotic weevil pests. *Microctonus aethioides* Loan (Moroccan ecotype) was released to control the alfalfa pest *S. discoideus* (Stufkens and Farrell 1980), *M. hyperodae* Loan for ASW (Goldson et al. 1992) and *M. aethioides* (Irish ecotype) for CRW (Gerard et al. 2006). All introductions were successful in suppressing damaging weevil populations, with both *M. aethioides* ecotypes providing natural control of what would otherwise have been major pests. An economic analysis of biological control of CRW in one region of New Zealand, found that control returned NZD14.78/ha/year and NZD6.86/ha/year for dairy and sheep & beef farms, respectively (Basse et al. 2015). Conversely, while *M. hyperodae* initially provided effective control of ASW (Barker and Addison 2006), recent evidence points to a breakdown in parasitoid efficiency and resurgence of weevil damage (Tomasetto et al. 2018).

The adult stage of *L. bonariensis* is susceptible to the entomopathogens *Microsporidium itiiti* Malone and *B. bassiana* (Barker et al. 1989), although they do not seem to provide effective control on the pest in the field. Isolates of *B. bassiana* have shown high levels of virulence against *S. obsoletus* (Nelson et al. 2015), but preliminary field trials showed limited success in the field (e.g. Brownbridge et al. 2006). Conversely, recent field trials of *Y. entomophaga* have demonstrated very good control of the adult stage of African black beetle (Mansfield et al. 2020).

An important strategy for protecting grasses (fescue and ryegrass) from insect pests in New Zealand is the development and use of fungal endophytes. Several *Epichloë* endophyte strains, producing different ranges of toxins that deter herbivorous insect feeding or oviposition (Schardl et al. 2013), are commercially available and their use is ubiquitous (Rodriguez et al. 2009; Schardl 2010). Such endophytes are effective in combatting ASW, African black beetle and porina, root aphids and pasture mealy bug (Popay and Hulme 2011) and show activity against grass grub (Ferguson et al. 2019).

Several biological control agents have been introduced and established in New Zealand for control of insect pests in improved grassland and alfalfa and are shown in Table 3. The list is compiled both from the Biological Control Agents Introduced to New Zealand (BCANZ) database, initially compiled from Cameron et al. (1989) and regularly updated as an online resource (Ferguson et al. 2007), along with published journal literature. It does not include predators, such as spiders (Vink et al. 2013), lacewings and ladybirds (e.g. *Coccinella undecimpunctata* L. (11 spotted ladybirds)), that may have some impact in improved grasslands, but which were not specifically introduced for that purpose. Feeding by the common starling (*Sturnus vulgaris* L.), an exotic bird species introduced to New Zealand during European colonisation, has been shown in some instances to reduce grass grub populations by 40–60%, with predation able to reduce larval populations below levels that caused yield losses (East and Pottinger 1975). However, the authors concluded that the effectiveness of control depended on the presence of high starling numbers, with only localised control achievable.

Table 3. List of insect biocontrol agents introduced into grasslands and alfalfa in New Zealand. Introductions undertaken as part of classical biological control programmes.

Insect species	Host attacked	Pest stage attacked	Biocontrol agent origin	Reference
Hymenoptera: Braconidae				
<i>Cotesia ruficrus</i> Haliday	<i>Agrotis ipsilon</i> , (Hufnagel)	Larvae	Pakistan	Cameron et al. 1989
<i>C. ruficrus</i>	<i>Chrysodeixis eriosoma</i> , (Doubleday)	Larvae	Pakistan	Cameron et al. 1989
<i>C. ruficrus</i>	<i>Mythimna separata</i> Walker	Larvae	Pakistan	Cumber et al. 1977
<i>Meteorus pulchricornis</i> (Wesmael)	Lepidopteran larvae (polyphagous)	Larvae	Europe	Berry and Walker 2004
<i>Microctonus aethiopoides</i> Loan	<i>Sitona discoideus</i> Gyllenhal	Adults	Morocco	Stufkens et al. 1987
<i>M. aethiopoides</i> Loan	<i>Sitona obsoletus</i> (Gmelin)	Adults	Ireland	Gerard et al. 2006
<i>M. hyperodae</i> Loan	<i>Listronotus bonariensis</i> (Kuschel)	Adults	South America	Goldson et al. 1992
<i>Aphidius eadyi</i> Stary, González & Hall	<i>Acyrtosiphon kondoi</i> Sinji	Nymphs	Europe	Cameron and Walker 1989
<i>A. eadyi</i>	<i>Acyrtosiphon pisum</i> Harris	Nymphs	Europe	Cameron and Walker 1989
<i>Aphidius ervi</i> Haliday	<i>A. kondoi</i>	Nymphs	Europe	Cameron and Walker 1989
<i>A. ervi</i>	<i>A. pisum</i>	Nymphs	Europe	Cameron and Walker 1989
<i>Bracon variegator</i> Spinola	<i>Coleophora frischella</i> L.	Larvae	Germany	Pearson 1989
Hymenoptera: Eulophidae				
<i>Chrysonotomyia trifolii</i> Erdos	<i>C. frischella</i>	Larvae	Germany	Pearson 1989
<i>C. trifolii</i> Erdos	<i>Coleophora mayrella</i> (Hübner) syn. <i>C. spissicornis</i>	Larvae	Germany	Pearson 1989

Discussion

International trade and tourism are seen as facilitating the global spread of invasive pests and plant diseases (Anderson et al. 2015; Early et al. 2016; Chapman et al. 2017; Evans et al. 2018; Seebens 2019) and associated loss of biodiversity (Paini et al. 2016; Courchamp et al. 2017; Li and Shen 2020). The threat posed by the movement of invasive species to China has been recognised (Xu et al. 2006; Wan and Yang 2016; Yan et al. 2017; Li and Shen 2020; Yu et al. 2020), with China’s Belt and Road Initiative (BRI) being viewed as increasing that risk (Liu et al. 2019; Seebens 2019). Climate change also represents a threat, as a driver for changes in the impact of pests and diseases (Huo et al. 2012a, b; Gutierrez and Ponti 2014; Deutsch et al. 2018), providing new opportunities for range expansion into regions that hitherto were unfavourable (Bebber et al. 2013; Robinson et al. 2020) and influencing the efficacy and options of management strategies (Gutierrez and Ponti 2014; Robinson et al. 2020). As noted by Robinson et al. (2020), climate change will alter the nature of vectors and pathways, the abiotic nature of the recipient environment and the biotic interactions in recipient communities. While the respective size difference of China and New Zealand is considerable, with diverse climate and environments, there will be regions in both countries that share similar climates under current and future temperature predictions, as indicated in Kriticos (2012). Temperate grass species widely grown in New Zealand are also grown in parts of China (e.g. ryegrass, oats). Similarly, alfalfa is grown across a wide range of environments in both China and New Zealand. Forage species suitability mapping shows there are several regions in the south and east of China where ryegrass is and can be grown (Hannaway et al. 2005). Where similar grasses and forages are established, that situation provides a potential opportunity for establishment of exotic

insect pests. Examples include the alfalfa pests, *S. discoideus* which is established in New Zealand and *H. postica* which is established in China. If *S. discoideus* were to establish in China, or *H. postica* in New Zealand, both species would likely become high impact pests without effective control options. In this respect, climate matching for key pests will be critical to understanding potential risks (e.g. Kriticos 2011; Roigé and Phillips 2020). The impact of an invasive pest is also potentially high, as both countries are classified as global biodiversity conservation hotspots within BRI (Seebens 2019; Li and Shen 2020). An analysis of the cost of invasive insect pests and pathogens found that China could experience significant economic impacts from establishment (Paini et al. 2016). China already has several high impact exotic pests (Suppl. material 3: Table S3) and the recent arrival of *S. frugiperda*, via Africa, but originally from the Americas, is a pest with a wide host range (Wu et al. 2019). The establishment *S. frugiperda* also highlights the dynamic nature of biosecurity, as invasion routes are not always directly from country of origin, but that secondary invasion pathways can facilitate the global spread of unwanted pests (Mansfield et al. 2019). An example of anthropogenic long-distance dispersal was the interception of adult *A. tasmaniae* in Tuscany, Italy in a sea container that came from New Zealand (Mazza et al. 2014). Similarly, importation of forages into China from overseas suppliers is significant, including grass and alfalfa as hay, powder and granules (Guo et al. 2019). In 2016, China imported forages from USA (1.29 M tonnes), Australia (0.22 M tonnes), Mongolia (0.075 M tonnes) and Spain (0.072 M tonnes). Other minor sources were Canada, Argentina, Europe and Central Asia (Guo et al. 2019). Inadequate biosecurity protocols, or slippage at the border, potentially provide a pathway for invasive pests associated with these commodities. As emphasised by Early et al. (2018), rapidly changing global trade and transportation patterns open invasion routes that pest species rarely travelled in the past.

The highest economically valued grasslands in New Zealand are very simple ecosystems (Goldson et al. 2020), comprised of generally less than five sown exotic plant species. Considerable resources in the form of weed control, fertiliser inputs and management are expended to maintain these pastures in a highly productive state. The associated invertebrate communities are also viewed as simple (Goldson et al. 2014; Goldson et al. 2020) and, while a few indigenous insects have been able to adapt and exploit these habitats (e.g. *C. giveni*, *Wiseana* spp.), some niches remain unfilled and potentially vulnerable to invasion by exotic pests that arrive unaccompanied by natural enemies which, in their country of origin, would exert some natural population regulation. This has been demonstrated by the establishment and impact of the scarab beetle *H. arator* and weevils *L. bonariensis* and *S. obsoletus* (CRW). The latter exploits clover root nodules and roots. Clover roots are also subject to quite severe attack by the endemic grass grub, but this is usually transitory in younger pastures which have not built up naturally occurring pathogens after cultivation and sowing. Therefore, clover roots were a 'vacant' feeding niche until CRW invaded New Zealand and was able to exploit that niche, facing little competition from existing fauna. First observed in 1996 (Barratt et al. 1996), over the subsequent 18 years CRW colonised nearly all of New Zealand's agricultural land. Prior to the release of the biocontrol agent *M. aethiopoidea* this led to a consider-

able reduction in clover survival and productivity. This resulted in increased costs to farmers to replace what was essentially a free nitrogen input and removing a facet of agriculture that allows New Zealand farmers to be internationally competitive. Another significant example of a vacant niche is alfalfa, currently largely free of invertebrate foliage feeders, but *H. postica*, could readily fill that niche should it arrive in New Zealand.

The 55 to 269 pests in alfalfa identified by Chinese researchers (Zhang et al. 2016; Zhang et al. 2018), substantially exceed those recognised in New Zealand (7). However, while biodiversity may be higher in China, it does not preclude significant impacts of invasive arthropods, such as has been shown with thrips *O. loti* in alfalfa (Zhang et al. 2017) and *S. frugiperda* in a range of crops (Wu et al. 2019).

Indigenous grasslands, while being more complex ecosystems, may also be threatened by new incursions. Displacement of indigenous invertebrates by exotic invaders is a reality, as evidenced by the Australian landhopper (*A. sylvaticus* Haswell), accidentally introduced to New Zealand and displacing native Talitridae (Duncan 1994). The potential threat to indigenous insect species from an invasive species competing in the same habitat or detrimentally modifying the habitat is unknown, but could possibly be predicted, depending on the degree of knowledge around biology, plant hosts and climate similarities. The Chinese grassland invertebrate fauna is very different from New Zealand grassland fauna and contains several species that are recognised as pests in China (e.g. Acrididae (Suppl. material 3: Table S3)). Their impacts could be significant in New Zealand grassland systems. Similarly, the same could be said for selected high-impact pests currently found in New Zealand, but not China (Suppl. material 4: Table S4).

There is potential for significant impacts arising from pest incursions, but entomophagous biocontrol agents, already established in the respective countries, may provide a level of control to ameliorate losses. Kiran et al. (2019) assessed the potential of the resident exotic parasitoid wasp fauna, already established in New Zealand, to provide biotic resistance against possible future pests. They concluded that the current exotic species could potentially suppress 442 pest species not yet occurring in New Zealand. However, this approach may not always work, as has been shown with the Moroccan strain of *M. aethiopoides* against CRW (McNeill et al. 2000) or the relatively host specific parasitoid *M. hyperodae* (Barratt et al. 1997).

Conclusions

While this review has identified some key grassland and alfalfa insect pests common to both New Zealand and China, there is a paucity of research that quantifies potential impacts on specific grassland or crops (e.g. alfalfa) in the respective countries. In addition, low impact pests in one country does not preclude their having a greater impact elsewhere, if they occupy underexploited niches, outcompete existing species or, through natural enemy release, have greater impacts on their plant hosts. While climate may limit range and impacts of an exotic species in the recipient country, field studies, whereby selected grassland species are established in climatically suitable regions in the country of origin,

provide the opportunity to identify and quantify pest impacts and address an important biosecurity issue. The sentinel plants concept, whereby plants growing in overseas locations can be used to identify and evaluate impacts of potential insect pest invaders, has proven to be valuable for identifying new pests and diseases for tree species (Vettraino et al. 2017; Eschen et al. 2019; Mansfield et al. 2019). Applying a similar approach to grassland and forage plants would seem logical for understanding impacts and providing information for pest risk analysis. From a New Zealand perspective, to remain internationally competitive grassland agriculture will rely on a limited number of high producing, but inherently vulnerable, plant species (e.g. ryegrasses, clovers and alfalfa). Any incursion and establishment of a pest able to utilise these plant species will threaten that competitiveness. Research that identifies potential high impact pests, prior to invasion and establishment, thereby provides early warning of pest risk. Understanding biology and behaviour also provides an opportunity to identify potential pathways by which a pest or pest complex could move between countries, as well as develop surveillance strategies for early detection in a recipient country. Furthermore, the sentinel plant concept allows for the identification of mitigation measures (e.g. plant resistance, biological control) that could be implemented in anticipation of an invasive pest's establishment in the recipient country.

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Supplementary material I

Table S1. The cultivated area and herbage yield of the main forage plant species in China

Authors: Mark R. McNeill, Xiongbing Tu, Colin M. Ferguson, Liping Ban, Scott Hardwick, Zhang Rong, Barbara IP Barratt, Zhang Zehua

Data type: species data

Explanation note: Cultivated area data obtained from the China Forage Data Report 2016. Mu is the unit of area used in China, with 15 mu corresponding to 1 ha, M = Million.

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Link: <https://doi.org/10.3897/neobiota.65.61991.suppl1>

Supplementary material 2

Table S2. The predominant use and the monetary values (NZD/CNY) of the main forage plant species in New Zealand

Authors: Mark R. McNeill, Xiongbing Tu, Colin M. Ferguson, Liping Ban, Scott Hardwick, Zhang Rong, Barbara IP Barratt, Zhang Zehua

Data type: species data

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Link: <https://doi.org/10.3897/neobiota.65.61991.suppl2>

Supplementary material 3

Table S3. List of main insect pest species found in grasslands and alfalfa in China

Authors: Mark R. McNeill, Xiongbing Tu, Colin M. Ferguson, Liping Ban, Scott Hardwick, Zhang Rong, Barbara IP Barratt, Zhang Zehua

Data type: species data

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Link: <https://doi.org/10.3897/neobiota.65.61991.suppl3>

Supplementary material 4

Table S4. List of main insect pest species found in grasslands and alfalfa in New Zealand

Authors: Mark R. McNeill, Xiongbing Tu, Colin M. Ferguson, Liping Ban, Scott Hardwick, Zhang Rong, Barbara IP Barratt, Zhang Zehua

Data type: species data

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